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Operational Based Vision Assessment Cone Contrast Test: Description and Operation

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1.0 SUMMARY

The work detailed in this report was conducted by the Operational Based Vision Assessment (OBVA) Laboratory, Aeromedical Research Department, Human Performance Branch, U.S. Air Force School of Aerospace Medicine, Wright-Patterson AFB, OH, with support from SpecPro Technical Services. The report describes the development and operation of an improved version of the Rabin cone contrast test (CCT) currently used by the Air Force for aircrew color vision screening. The new OBVA CCT is differentiated from the Rabin device primarily by hardware, test procedures, and analysis techniques. Like the Rabin CCT, the OBVA CCT uses colors that selectively stimulate the cone photoreceptors of the standard human observer. The OBVA CCT builds on the success of the Rabin CCT through the use of highly accurate color display calibration, use of Landolt C optotypes to simplify response entry, and adoption of adaptive threshold estimation procedures well-described in the research literature. This report summarizes the color calibration procedure and operation of the OBVA CCT and presents preliminary data demonstrating the validity of the new test for identifying and classifying protanomalous and deuteranomalous (red/green) color deficient individuals.

2.0 PURPOSE/BACKGROUND

The Operational Based Vision Assessment cone contrast test (OBVA CCT) is designed to detect abnormalities and characterize the contrast sensitivity of the color mechanisms of the human visual system. The OBVA CCT will increase the reliability and efficiency of these metrics, which are widely used in medical and occupational environments.

2.1 Purpose and Area of Use

There is a long history of color vision testing dating back to the late 19th century. For a review, see Melamud et al. [1]. Here we are only interested in computer-controlled monitor-based tests that can reduce the test time, limit test administrator time, and eliminate test administrator error. In addition, because each instance of the test can use a randomized stimulus presentation order, these systems can greatly reduce the possibility that studying for the test can improve scores. This capability is particularly import in selection and retention of individuals for occupations where normal color vision is a requirement.

2.2 New Techniques Used in the OBVA CCT

It is generally accepted that color-normal observers have three color mechanisms: one achromatic mechanism that sums the input from the cones and two cone-opponent mechanisms that take differences. It is also generally accepted that one of the opponent mechanisms takes the difference between the long-wavelength cones or L cones and the middle-wavelength-sensitive cones or M cones (L-M mechanism) and that the second opponent mechanism takes the difference between the short-wavelength-sensitive cones or S cones and the sum of the L and M cones (S-LM mechanism).

By definition, color vision tests are designed to measure the behavior of the cone-opponent mechanisms. Most monitor-based tests attempt to isolate the cone-opponent mechanisms by designing test stimuli that change the contrast to the cone-opponent mechanisms

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with minimal contrast change to the achromatic mechanism. In addition, random achromatic contrast is often added to the background to further limit detection by the achromatic mechanism. Although the opponent process was not fully described until the 1950s, the most famous of these tests is the Ishihara plates, which were developed in the early 20th century [2]. Tests that are more modern use computer monitors to generate the stimuli and use static or dynamic achromatic noise to desensitize the achromatic mechanism. However, the logic behind the design of most tests is similar to that developed by Ishihara.

The OBVA CCT is most similar to the Rabin CCT [3], which is currently used for selection and retention in the U.S. Air Force (USAF). The new OBVA CCT is differentiated from the Rabin device primarily by hardware, test procedures, and analysis techniques. Like the Rabin CCT, the OBVA CCT uses colors that selectively stimulate the cone photoreceptors of the standard human observer. By definition, these stimuli must affect both the cone-opponent and achromatic mechanisms. For example, a stimulus that stimulates only the M cones will generate a negative output in the L-M mechanism and S-LM mechanism and a positive output in the achromatic mechanism. Because of this, the current OBVA CCT has a fundamentally different design than most monitor-based tests, which are designed to change the contrast to the cone-opponent mechanisms with minimal contrast change to the achromatic mechanism.

The techniques used to stimulate a single cone mechanism are well known. The research of Smith and Pokorny [4], which provided an estimate of the spectral sensitivity of the human cones, greatly facilitated this technique, and the mathematics needed to implement the technique were published by Estevez and Spekreijse in 1982 [5].

Because a test stimulus in the OBVA CCT stimulates multiple mechanisms, it may seem difficult for this system to measure the sensitivity of the cone-opponent mechanisms, which as stated above is the purpose of all color vision tests.   However, if the propositions listed below are true, then we can measure the sensitivity of the cone-opponent mechanisms:

1. When the sensitivities of detection mechanisms are sufficiently different, contrast threshold (the contrast required to perform at a criterion level) is primarily determined by the most sensitive mechanism.
2. Cone-opponent mechanisms are more sensitive than the achromatic mechanism.

The first proposition is supported by a wealth of psychophysical experiments and can be found in many textbooks [6]. Because the relative sensitivity of the mechanisms is determined by the spatiotemporal properties of the test stimulus, the second proposition is only true for certain stimuli. In general, stimuli with large sizes and long durations increase the sensitivity of the color opponent mechanisms relative to that of the achromatic with the L-M mechanism being the most sensitive. For example, Cole et al. [7] showed that the L-M mechanism could be one order of magnitude more sensitive than the other mechanisms. Furthermore, several studies have shown that both the Rabin CCT and the OBVA CCT are very effective at identifying and classifying color deficiency [8] although there are clearly differences between them that should be examined [9].

The OBVA CCT is primarily concerned with characterizing the L-M mechanism, which represents greater than 99% of genetically determined color vision deficits. The primary metrics of the OBVA CCT are the L cone, M cone, and S cone contrast thresholds and, if desired, the achromatic contrast threshold. To meet current USAF vision screening policy, these values should be scaled for reporting purposes such that the cone contrast corresponding to the pass/fail

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criterion is at a value of 75. However, the details of this scaling procedure remain to be determined.

Because the OBVA CCT includes an achromatic contrast test, a normalized cone contrast threshold, which has the potential to improve the classification of color deficiency, can be used. This scoring method has not been implemented in the current software, but is presented in the example data below. The normalized cone contrast threshold results from the division of L cone and M cone thresholds of observers by their achromatic threshold. If both ratios are less than 1, the observer is determined to have a normal L-M mechanism. In this instance, the L cone and M cone thresholds can be used to characterize the sensitivity of the mechanism. If the ratio is greater than 1, the individual is determined to have an abnormal L-M mechanism. The L-M sensitivity of mildly abnormal individuals (anomalous trichromats) can also be characterized using this OBVA CCT.

Although S-LM deficits represent a tiny percentage of genetically determined color deficits they represent a large proportion of acquired deficits. Fortunately, because modulation along the S cone vector selectively stimulates the S-LM mechanism, S cone thresholds provide a useful metric to characterize this color opponent mechanism without normalization. While this method is not novel, it is included in the device for completeness.

3.0 DETAILED DESCRIPTION

3.1 Display Characterization

Display characterization is required to accurately determine the RGB values of the graphics card needed to generate the desired cone excitation levels on the monitor. The display is characterized using a standard monitor model [10], which requires specifying the spectral sensitivity of the cones and measuring the emission spectra and intensity-response function of the monitor primaries. In short, after compensating for RGB to intensity nonlinearity, stimulus cone excitation $\boldsymbol{e}(l,m.s)$ for a particular set of monitor primary intensities $\mathbf{w}$ (r, g, and b) is determined by the matrix equation

$$\boldsymbol{e} = \mathbf{M}\mathbf{w}$$

The primary intensities required to generate a particular cone excitation levels is determined by

$$\mathbf{w} = \mathbf{M}^{-1}\boldsymbol{e}$$

This application uses the CIE 2006 LMS functions (2 degree) to specify the spectral sensitivity of the L, M, and S cones of a standard observer [11]. The tabulated functions can be downloaded at **http://www.cvrl.org**. The emission spectra and intensity-response of the monitor primaries were measured using a spectroradiometer (Maya 2000 Pro, Ocean Optics, Dunedin, FL).

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3.2 Cone Contrast

Stimuli colors are described by vectors in cone contrast space whose axes correspond to those colors that selectively stimulate the three cones of a normal human observer. Cone contrast $c(l,m,s)$ is computed by taking the difference between the cone excitation levels of a stimulus $e(l,m.s)$ and the cone excitation levels of a uniform background $b(l,m.s)$ and dividing the difference by the cone excitation levels of the background:

$$c(l,m,s) = \frac{e(l,m,s) - b(l,m,s)}{b(l,m,s)}$$

A stimulus color in this space can be described by a vector $v = (cd_L, cd_M, cd_S)$, which has a length c and direction $d = (d_L,d_M,d_S)$. For example, $d = (0, 1, 0)$ would incrementally stimulate only the M cone.

3.3 Stimulus Parameters

BACKGROUND LUMINANCE AND CHROMATICITY: The background will have a luminance of 100 candelas/m^2 and a D65 (daylight) chromaticity.

SPATIAL PARAMETERS OF THE OPTOTYPE SET: The optotype set will consist of four Landolt C stimuli with the gap rotated to up, down, left, and right angles.

OPTOTYPE SIZE: The optotype will subtend 50 arc minutes at the viewing distance. This relatively large optotype (20/200 Snellen) is used to maximize the sensitivity of the color opponent mechanisms relative to the achromatic mechanism.

OPTOTYPE PRESENTATION: Only one optotype will be presented in a trial. It will be flashed for 3 seconds and then extinguished.

NUMBER OF CHOICES: The observer will respond to one out of four conditions corresponding to the orientation of the Landolt C gap.

RESPONSE BOX: Four buttons in an up, down, left, right arrangement will be used.

VIEWING DISTANCE: The viewing distance will be 3 feet.

3.4 Psychophysical Method

The OBVA CCT uses adaptive methods that use the prior responses of an observer to generate the contrast level of the current trial. The benefit of these procedures is that they reduce the number of experimental trials required to estimate observer performance metrics for criterion accuracy level. The procedures use Bayesian statistics to fit the response data to a psychometric function (probability correct vs. contrast). Psychometric functions are fit using four parameters: threshold, slope, lapse rate, and chance level. Because the chance level is determined by the

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number of choices in the task, it is fixed prior to data collection. In this application, there are four choices, so the chance level is ¼.

The OBVA CCT allows the selection of two different adaptive methods: the psi method [12], which can estimate threshold, slope, and lapse rate (or any combination), and the Quest procedure [13], which estimates threshold and requires that the slope and lapse rate are set prior to data collection. The two methods are roughly equivalent in terms of efficiency and reliability. The Quest method is probably simpler to implement, while the psi method may be less sensitive to finger errors, and can also provide an estimate of the slope in addition to an estimate of threshold (although estimating slope requires many more trials).

4.0 MANNER AND PROCESS OF MAKING AND USING THE OBVA CCT

The OBVA CCT uses a consumer off-the-shelf computer, monitor, and response pads. This hardware is integrated with custom software that generates the stimuli, collects responses, and analyzes the results as outlined in section 3.0 above. Although the primary value-added component of the system is the custom software, there was a substantial effort aimed at determining the hardware that would provide the most accurate and reliable metrics. These design considerations are discussed in section 5.0.

It is critically important that the observed screen colors are accurate. As discussed section 3.0, this is accomplished by parameterizing a monitor model that quantifies the relationship between graphics card RGB values and cone excitation levels. This monitor model will be used for all implementations of the OBVA CCT, and to measure accurate performance metrics that are the same for all implementations of the OBVA CCT, we must make sure that the properties of the deployed monitors are standardized. However, monitor properties can change over time and even between monitors from the same manufacturer. Because of this, the system will include a colorimeter that can test the system to see if it is in the proper state. If the system is out of calibration, the colorimeter and custom software can be used to return the system to the standard state.

5.0 ALTERNATIVES

As stated in the section 2.0 of this document, the Rabin CCT [3] is most similar to the new OBVA CCT. Although both tests use cone contrast metrics to characterize color vision abnormalities, we believe that the OBVA CCT represents a substantial improvement of the hardware and test procedure compared to the Rabin CCT. It should be noted that the Rabin CCT is currently used for the selection of aircrew in the USAF and that the current OBVA CCT was developed to replace it.

One of the primary limitations of the Rabin CCT is hardware. It has been clearly demonstrated that observed colors on the Rabin CCT change dramatically with head movement. These changes will, of course, invalidate the test metrics. More generally, any hardware that reduces the reliability and accuracy of the background and test colors would also significantly detract from the usefulness of the OBVA CCT. Because the current Rabin CCT uses inexpensive displays, the colors will be less stable over time and across different devices than a high-quality monitor. The OBVA CCT mitigates these problems by using a high-quality in-plane-switching monitor, which has stable colors over wide angles and over time.

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Furthermore, the psychophysical procedures used to estimate thresholds in the OBVA CCT are based on published techniques that have wide use in academic research, whereas the Rabin CCT uses a custom procedure. In previous research, a Monte-Carlo simulation technique was used to compare the Quest procedure implemented in the OBVA CCT to the custom staircase implemented in the Rabin CCT. The results demonstrated that the Quest procedure is more efficient and more accurate [14].

The OBVA CCT uses a Landolt C optotype, which has a long history in visual testing. It was introduced in 1888 by Edmund Landolt and is currently the standard in most European countries. It has well-defined simple properties when rotated (nothing changes except an angular component). It maps intuitively onto an up, down, left, right response input device, thus decreasing finger errors. Because the optotype must be large to increase the relative sensitivity of the cone-opponent mechanisms, observers must fixate at points around the ring to minimize contrast thresholds. The Landolt C optotype has the desirable feature that the optimal fixation set used to detect the location of the gap is the same for all orientations tested. This should lower performance variability between observers due to different search strategies. We believe that this represents a significant improvement over the Sloan letters used in the Rabin CCT. Although the Sloan letters were a very effective solution for the use of paper-based charts and verbal responses, the Landolt C is more effective for implementation on an electronic display and a four-alternative forced-choice keyboard response, while still retaining the simplicity of an easy-to-describe letter.

To test contrast threshold, it is important that the contrast sensitivity of the observer is maintained at a constant level. It is well known that changes in local luminance or contrast can alter contrast sensitivity or contrast gain of the visual system [15]. In the OBVA CCT, we use stimuli that are near the observer's contrast threshold so the test targets should not materially modify the observer's contrast sensitivity. In addition, the test background is uniform (zero contrast).

Finally, the response input method used in the OBVA CCT allows the observer to maintain fixation in the low-contrast area around the test image. In the Rabin CCT, observers use a mouse to point to a letter on a relatively high contrast letter list to indicate their choice. Switching fixation between the high-contrast letter list and the low-contrast targets as is required in the Rabin CCT can potentially alter the contrast sensitivity of the observer and add variability or bias to the measured metrics. The response input method of the OBVA CCT requires less time than the mouse-based procedure used in the Rabin CCT. Therefore, the OBVA CCT can obtain more responses in a fixed time period than the Rabin CCT. This results in a more time-efficient testing procedure, and along with the increased efficiency of the psychophysical procedure, the OBVA CCT is significantly more efficient than the Rabin CCT.

The combination of precise calibration, highly efficient psychophysical techniques, scoring method, response entry, and normative data described in this OBVA CCT will not only support highly accurate color vision classification without increasing test time, but is also precise enough to track small changes in color vision, which has not been possible with previous tests.

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6.0 EXAMPLE DATA

As stated above, stimuli colors are described by vectors in cone contrast space $v = (cd_L, cd_M, cd_S)$, which has a length c and direction $d = (d_L, d_M, d_S)$. However, for this data set we are not interested in measuring contrast threshold along the S cone direction (where color vision deficits are rare), so the three-dimensional vectors are projected onto the LM plane, which results in two-element vectors. The vectors of the three stimuli used in this study are

L	$d = (1, 0)$
M	$d = (0, 1)$
A	$d = (0.71, 0.71)$

The unit vectors $c = 1$ for the three stimuli are shown in Figure 1.

For a normal observer with CIE 2006 LMS spectral sensitivity functions [11], the L color stimulates only the L cone and the M color stimulates only the M cone. The A color stimulates both cones equally.

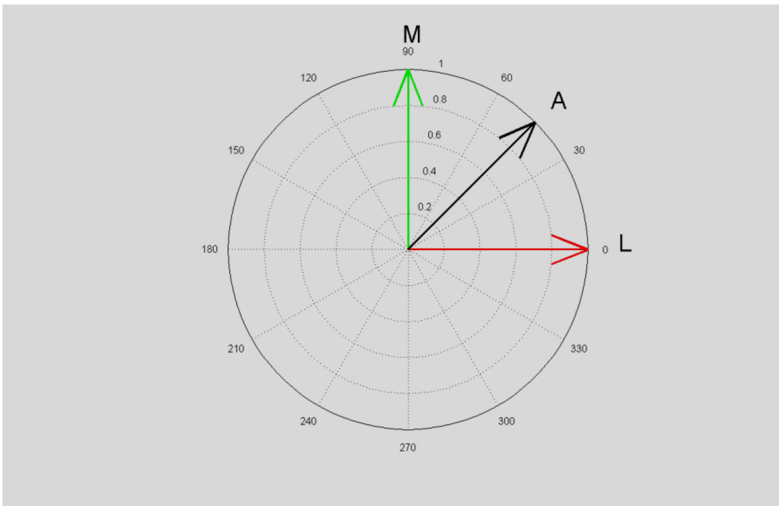

Figure 1. Unit vectors for the three colors used in this study.

Histograms of contrast thresholds for the L, M, and achromatic colors for 98 observers are shown in Figure 2. The histogram in the lower right was generated by dividing the L and M contrast threshold of each observer by his/her achromatic contrast threshold, $L_{norm} = L/A$, $M_{norm} = M/A$ and taking the maximum of the normalized values. We will refer to this metric as *maxLM*.

Examination of the lower right chart in Figure 2 reveals two easily separated distributions with a gap at approximately zero. Because the axis is logarithmic, zero corresponds to a normalized cone contrast of 1. Observers with *maxLM* values less than 1 (negative logarithmic values) are more sensitive to L and M colors than achromatic and these observers are classified as color normal. The results are illustrated with white bars. Observers with *maxLM* values greater than 1 (positive logarithmic values) are classified as color abnormal.

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It is well known that there are three major classes of color abnormalities corresponding to the three cone types. Again, here we are only interested in L-M mechanism abnormalities, which consist of L cone abnormal individuals called *protans* and M cone abnormal individuals called *deutans*. This procedure distinguishes protans from deutans by examining the $ML_{ratio} = M_{norm}/L_{norm}$. If the ratio is less than 1, observers are classified as a protan and are illustrated using red bars in the figure. If the ratio is greater than 1, observers are classified as a deutan and are illustrated using green bars in the figure.

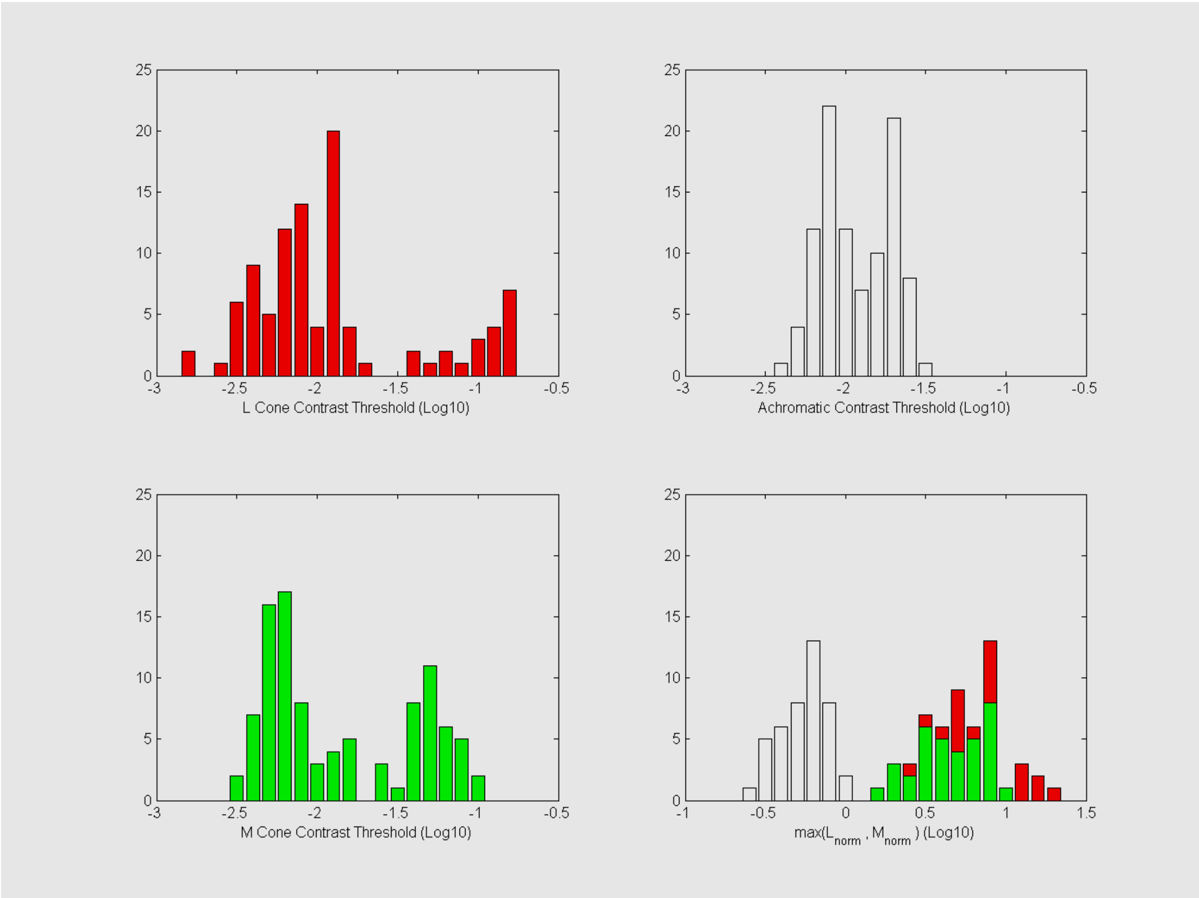

Figure 2. Histograms of the contrast thresholds for the L (upper left), M (lower left) and achromatic (upper right) colors for 98 observers. *The lower right chart shows the result of the analysis described in the text.*

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Figure 3 shows the same data using a polar plot. The figure clearly illustrates the segregation of color normal (black), protan (red), and deutan (green) individuals. In this figure, the radius is equal to the maximum of the normalized L and M contrast threshold (the horizontal axis in lower right chart of Figure 2) and the angle is equal to $\tan^{-1}(ML_{ratio})$. For abnormal individuals the radius indicates the severity of the abnormality. For normal individuals the distance from the origin represents improved contrast sensitivity.

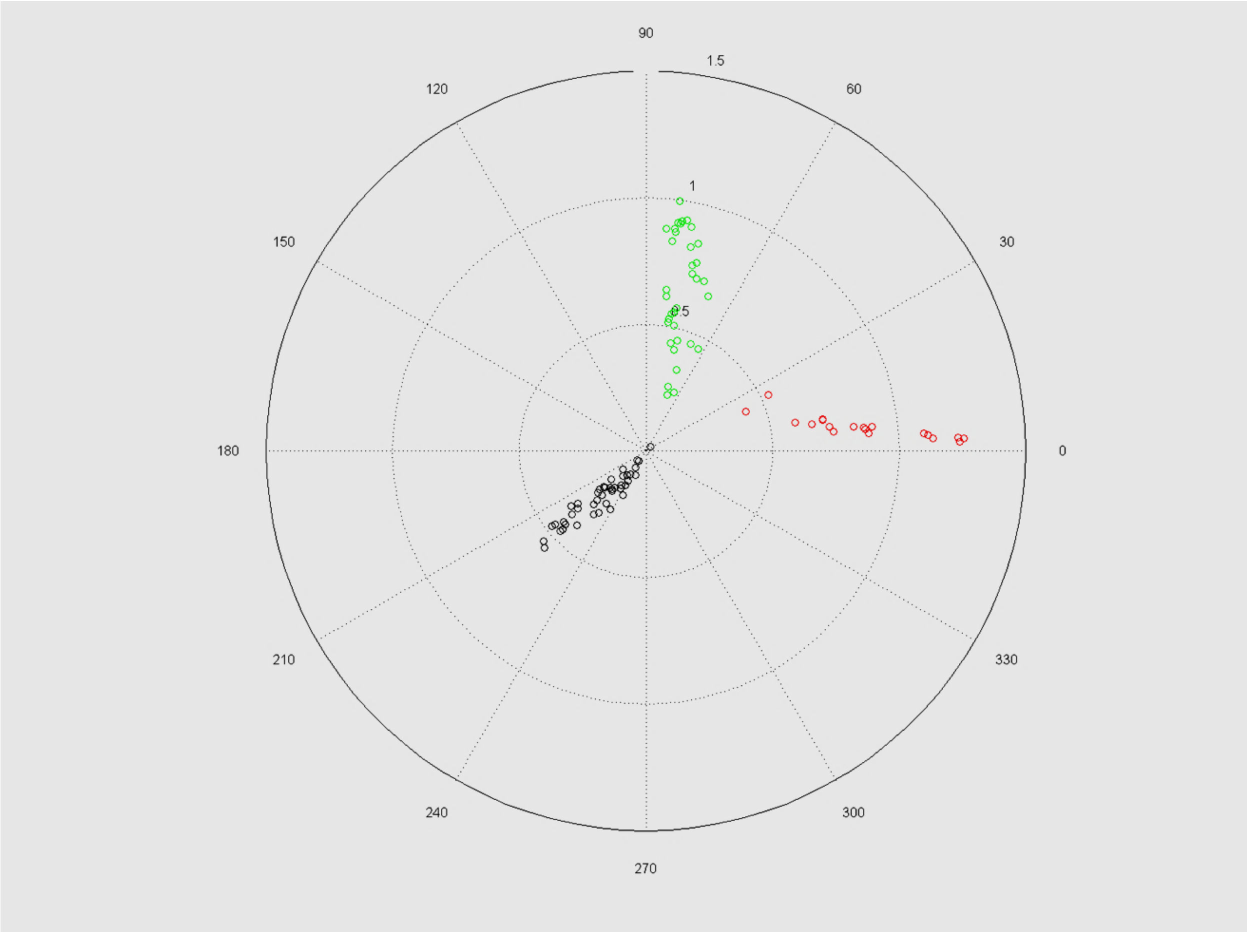

Figure 3. Polar plot of classification data. *The radius of each data point is equal to the maximum of the normalized L and M contrast threshold for the observer and the angle is equal to* $\tan^{-1})(ML_{ratio})$.

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LIST OF ABBREVIATIONS AND ACRONYMS

CCT	cone contrast test
L	long wavelength
M	middle wavelength
OBVA	Operational Based Vision Assessment
S	short wavelength
USAF	U.S. Air Force

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